Legumes production in Europe to mitigate agricultural emissions in a global perspective

Prudhomme Rémi*[1,2,3], Brunelle Thierry †[1,2], Dumas Patrice‡[1,2], and Zhang Xin[4]

[1]Centre international de recherche sur l'agriculture et le développement, CIRAD
[2]Centre international de recherche sur l'environnement et le développement, CIRED
[3]Agroparistech
[4]Princeton Environmental Institute, Princeton University

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Abstract

Reactive nitrogen is an indispensable nutrient for agricultural production, since half of the crop production depends on human nitrogen fertilization, but reactive nitrogen also contributes to climate change through nitrous oxide emissions. Legumes fix nitrogen that can be used by subsequent crops, and emit less nitrous oxide than non legume crops. Ruminants use important areas of land, notably pastures and are associated to emissions of methane through enteric fermentation and methane and nitrous oxide during manure management. Introducing legumes to replace livestock could allow for reductions of Green House Gas (GHG) emissions, although this effect depends on how this introduction modifies livestock and cropland intensification and extensification. We evaluate the impacts of legume introduction in Europe on global agricultural emissions and production using a global agricultural intensification model: the NLU (Nexus Land-Use). We decompose effects of a demand side scenario representing a shift of animal protein to legume protein on GHG emissions taking into account indirect effects and characteristics of legumes. We also decompose effects of this scenario on the calorie price of the representative crop. For a 11.4kg/capita/year legumes introduction scenario, the net effect is an emission decrease of 100 million tCO2eq/year. It also decreases price of crops by % in 2050. The reduction of global demand decreases GHG emissions by 600 million tCO2eq/year. This reduction is partly compensated by an increase of emissions per unit of production, as livestock extensification leads to emission increases of 550 million tCO2eq/year. The importance of the indirect livestock extensification effect is caused by the low efficiency of extensive systems and the exogeneity of forest areas evolutions in the NLU. It emphasises the importance of taking into account indirect effects because of their major role in emission changes.

1 Introduction

Reactive nitrogen (Nr) is an indispensable nutrient for agricultural production since half of the production depends on human fertilization of nitrogen (Ladha et al., 2005) and 70% of production increase in the past four decades is due to yield increase (FAOSTAT, 2011). Reactive nitrogen is also responsible

*prudhomme@centre-cired.fr
†brunelle@centre-cired.fr.fr
‡dumas@centre-cired.fr

of terrestrial, aquatic, air and atmospheric Nr pollution. These damages are estimated at 0.3% to 3% of global GDP (Bodirsky et al., 2014b). While planetary boundaries of the nitrogen cycle are already estimated to be transgressed at both global (Rockström et al., 2009) and regional scales (de Vries et al., 2011), sources of reactive nitrogen could continue to grow to 2050 by 232 $TgN.yr^{-1}$ for the B1 SRES scenario (Bodirsky et al., 2014a). For this reason, ambitious mitigation strategies of Nr pollution need to be evaluated.

Mitigation options of nitrogen pollution can be implemented through supply-side measures, such as improvement of nitrogen use efficiency (NUE), or demand-side measures, such as reduction of waste and shift toward less consumption of animal products. NUE can be improved through several options such as genetic improvement or precision farming (Zhang et al., 2015). Substitution of synthetic nitrogen from Haber-Bosch synthesis by biological fixation from legumes is still controversial on its efficiency to reduce GHG emissions (Cassman et al., 2002). Legumes introduction in rotation provide nitrogen for the next culture by stocking biologically fixed nitrogen in residues and by increasing nitrogen in harvested grain. Nitrogen left by legumes, however, may leach more in maize-soybean system compared to maize alone system (cited in Cassman et al. 2002). Legumes also can have lower yields than other crops, such as cereals and thus cause extensification.

Europe is dependent on leguminous crops imports, in particular soybean used as livestock feed. The debates on nitrogen protein import dependence by the European commission concluded that increasing domestic production would be important (Häusling, 2011). In addition, the last Common Agricutural Policy (CAP) reform, in 2015, through green instruments like the Green Direct Payment which considers legumes as area of particular interest for ecology (CAP, 2013). Policies pushing for legumes production increase could therefore be implemented in the future in Europe. The evaluation of the environmental impacts of such a policy is therefore relevant.

Previous studies evaluating legume impacts on environment focused on Europe did not take explicitely into account indirect effects associated to the land scarcity increase following legumes area increase (Nemecek et al., 2008). At the global scale, Bodirsky et al. (2014a) highlighted the importance to combine different mitigation options to reduce nitrous oxide emissions and the need to take into account indirect drivers of agricultural emissions such as population and diets changes as described, for example, in SSPs.

Here, we focus on a mitigation option on the demand-side with legumes introduction in Europe replacing ruminant proteins. To evaluate this strategy, we modify the NLU model to add a nitrogen balance, in particular legumes fixation. The modified model is used to compare a scenarios of ruminant/fieldpea protein substitution in food diet with a reference scenario.

To understand the processes behind the results, the effect of the diet substitution on GHG emissions is decomposed in three effects. The scale effect corresponds to the overall productions changes, the composition effects corresponds to changes in the share of legumes nitrogen fixation, and "technological" effects is associated to changes in emission intensity.

2 Method

2.1 Nitrogen fertilisation in the NLU model

The NLU model is a partial equilibrium model in which the agricultural sector is divided into 12 regions, inter-connected with each other by international trade. The model represents agricultural intensification processes for crop and livestock production by simulating inputs-substitution between: land and fertiliser for the crop sector; and grass, food crops, residues and fodder for the livestock sector.

The cropland-fertilizer substitution elasticity is not parametrized, but results from a cost-minimization program depending on the relative land-fertiliser prices. The shadow price of land (= land rent) is endogenously computed in the NLU model, as the lagrangian multiplier associated to the land constraint in the cost-minimization program. The fertilizer price is a global variable driven by exogenous scenarios described in Brunelle et al. (2015).

Two categories of crops are distinguished in NLU: "dynamic" crops, including most cereals, oilseeds, sugar beet and cassava, and "other" crops with sugar cane, palm oil, vegetables and fruits, some fodder crops and other remaining crops. All categories of crops are aggregated weighted according to their edible energy content values. The evolution of cultivated areas and yields for "other" crops are determined exogenously. On the other hand, "dynamic" crop yields are endogenously determined, taking into account biophysical constraints and the amount of fertilizer used (for more details, see Souty et al. (2012)).

The following nitrogen balance is used to determine N_{inorg} (Zhang et al., 2015):

$$N_h + N_{losses} + N_{lef} = N_{inorg} + N_{manure} + N_{rot} + N_{fix} + N_{deposition} \tag{1}$$

With N_h the harvested nitrogen, N_{losses} the loss nitrogen, N_{lef} quantity of nitrogen left for the next rotation by legumes, N_{inorg} the inorganic nitrogen, N_{manure} the manure nitrogen, N_{rot} nitrogen quantity given by the previous rotation legumes, N_{fix} the biologically fixed nitrogen, $N_{deposition}$ the nitrogen quantity deposed from the atmosphere.

$N_{deposition}$ is constant per unit area, N_{manure} is rescaled depending on livestock production, using tier 1 coefficients. We note α_N^{harv} the harvested nitrogen per calorie, ρ the representative "dynamic" crop yield in energy and and α_N^{fix} the fixed nitrogen per calorie:

$$\begin{aligned} N_{fix} &= \rho\ \alpha_N^{fix} \\ N_h &= \rho\ \alpha_N^{harv} \end{aligned}$$

A non-linear fertilizer response function $NC(\rho)$ is used to determine total nitrogen input, allowing to determine the demand in synthetic nitrogen, noted $IC(\rho)$ which and is equal to N_{inorg} in the balance:

$$IC(\rho) = NC(\rho) - (\alpha_N^{fix}\rho + N_{manure} + N_{deposition}) \tag{2}$$

The intensification level is determined by a micro-economic criteria of equality the marginal cost with marginal benefit:

$$IC'(\rho) = \frac{p_{cal}}{p_\chi} = NC'(\rho) - \alpha_N^{fix} \tag{3}$$

with p_χ the price of inputs and p_{cal} price of calorie produced.

The NUE and losses are available as:

$$\begin{aligned} NUE &= \frac{N_h}{NC(\rho)} \\ N_{losses} &= (1 - NUE)NC(\rho) \end{aligned}$$

2.2 Scenarios

In the reference scenario, consumption per capita based on the 2050 FAO projection (Bruinsma, 2003). The potential yields distributions do not evolve in this scenario. In the second scenario, ruminant protein consumption is shifted to legumes protein consumption in Europe. Two variants are considered: in the first one, legumes consumption in Europe increases from its current level of 2.7kg/capita/year to the world average of 6.8kg/capita/year in 2030; in the second variant, legumes consumption in Europe is projected to reach the canadian objective of 11.4kg/capita/year defined in its food policy of legumes consumption in 2030.(Fig.1) The canadian food policy is used because Canada and Europe development levels are similar and because the canadian objectives is supposed to be both ambitious and achievable. Field pea is considered to replace ruminant products in the european context.

To determine the decrease of ruminant protein consumption equivalent to the increase of pea, we use a coefficient of protein content per crop energy content based on FAOSTAT Food Balance

Sheets (FAOSTAT, 2015), and protein digestibility coefficients of 0.8 for vegetal proteins and 0.9 for animal proteins. Field pea introduction changes the distribution of the NLU "dynamic" representative crop potential yield. Nitrogen content, share of left nitrogen and biologically fixed nitrogen are also modified. See Supplementary material for details.

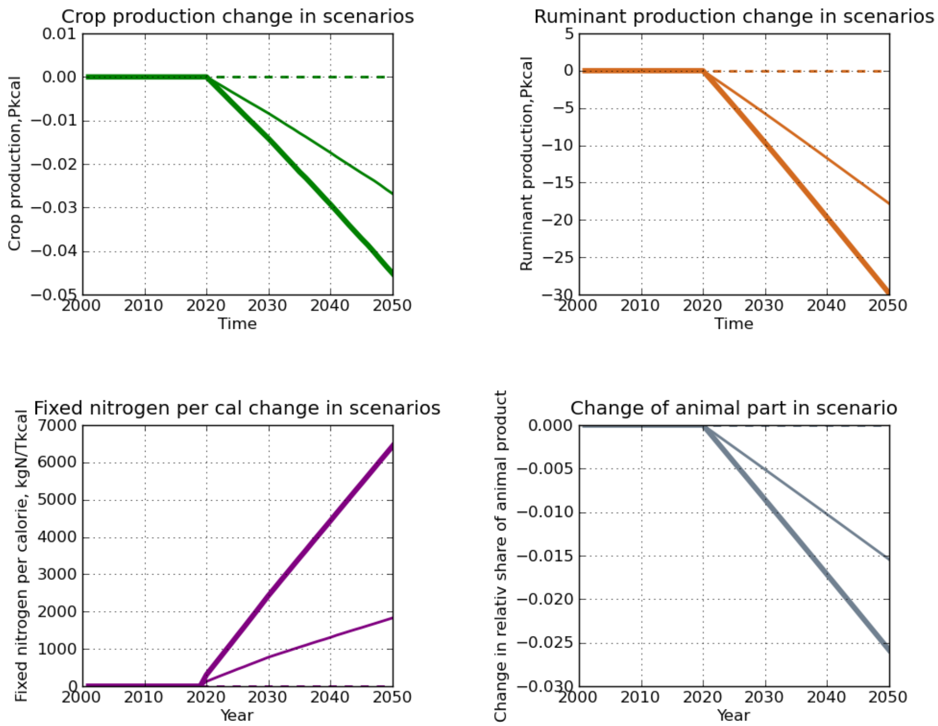

Figure 1: Change of parameters influenced by the legume change in the different scenarios compared to the base line: vegetal production change, ruminant production change, change of the representative crop fixation per calorie coefficient and ruminant share in diet change.

2.3 Decomposition of GHG emissions and agricultural production

Replacement of ruminant products by legumes triggers many changes, in particular a change in the distribution of potential yields and in the nitrogen balance, a decrease in ruminant production, but also changes in agricultural and livestock intensification as well as changes in trade. To better understand how these changes influences emissions, we decompose emissions change between a scale effect, a composition effect and a technological effect.

In the decomposition analysis, different methods can be used. To study shift in production share between leguminous and other productions, Index Decomposition Analysis (IDA) is prefered to structural decompostion analysis (Hoekstra and Van den Bergh, 2003). To explicitly decompose effects of increased areas of leguminous on emissions, we use a perfect decomposition that does not contain residual term. To allocate residues of pure effects factors, we use the Logarithmic Mean Divisia Index(LMDI) method developed in Ang and Liu (2001). These methods are used in energy studies to decompose decreasing GHG emissions of a energy mix change in three effects: change in total production called the scale effect, shifts in composition, called the composition effect and change of emission factors, called the technology effect (Kaya and Yokobori, 1998). A diet shift has similarities with an energy mix change that allow us to adapt LMDI method to agricultural sector: a replacement of plant by ruminant calories changes the overall demand in calories, changes the diet food composition and changes the agricultural production technology.

The scale effect is usually described as the impact of a policy on the size of the economy overall production. Usually evaluated using Gross Domestic Production (GDP), here the change is described in term of change in total production in energy equivalent.

The composition effect is usually described as the impact of a technology share change. There are many possible changes in shares that could be considered here. Since we are interested by legumes fixation of nitrogen, the share considered is the proportion of nitrogen brought by biological fixation of legumes in the total production.

The technology effect is usually the effect of emissions per unit of energy consumption change. Here emissions per nitrogen unit of leguminous produced is used to take into account indirect emissions of legume introduction such as land-use change emissions or intensification emissions in other part of the world.

To fully described impacts of legume introduction on each GHG (methane, nitrous oxide and carbon dioxide), emission changes are decomposed as:

$$\Delta E_i = E_i - E_{i_0} = \Delta E_{i_{Scale}} + \Delta E_{i_{Tech}} + \Delta E_{i_{Compo}} \tag{4}$$

with E_i the GHG emissions in the diet shift scenario and E_{i_0} the GHG emissions in the reference scenario, $\Delta E_{i_{Scale}}$ the emission change attributed to scale effect, $\Delta E_{i_{Tech}}$ the emission change corresponding to technology effect and $\Delta E_{i_{Compo}}$ the emission change of the composition effect.

For each GHG emission, we decompose as following:

$$E_i = \underbrace{Prod}_{\text{Scale}} \quad \underbrace{\frac{N_{fix}}{Prod}}_{\text{Composition}} \quad \underbrace{\frac{E_i}{N_{fix}}}_{\text{Technology}}$$

where $Prod$ is the overall vegetal production in equivalent energy, N_{fix} is the quantity of nitrogen biologically fixed by legumes.

By applying the LMDI analysis to identify each effect (Ang and Liu, 2001), we obtain the decomposition equations:

$$\Delta E_{i_{Scale}} = L(E_i, E_{i_0}) \quad (\ln(Prod) - \ln(Prod_0)) \tag{5}$$

$$\Delta E_{i_{Compo}} = L(E_i, E_{i_0}) \quad \left[\left(\ln(\frac{N_{fix}}{Prod}) - \ln(\frac{N_{fix_0}}{Prod_0})\right)\right] \tag{6}$$

$$\Delta E_{i_{Tech}} = L(E_i, E_{i_0}) \quad \left[\left(\ln(\frac{E}{N_{fix}}) - \ln(\frac{E_0}{N_{fix_0}})\right)\right] \tag{7}$$

with

$$L(E_i, E_{i_0}) = \frac{E_i - E_{i_0}}{\ln(E_i) - \ln(E_{i_0})}$$

2.4 Decomposition of calorie price

The same decomposition than previously is applied with calorie price change.(Fig.4) A scale effect represents change due to variation of vegetal production. A composition effect represents changes due to variation of share of fixed nitrogen in overall nitrogen source. Finally technological effect represents price variation per unit of legumes introduce.

3 Results

The diet shift decreases slightly use of nitrogen fertilizer of less than one percent (Fig.2). It doesn't change the fertilizer consumption trend which increase from around 54% of the overall nitrogen source

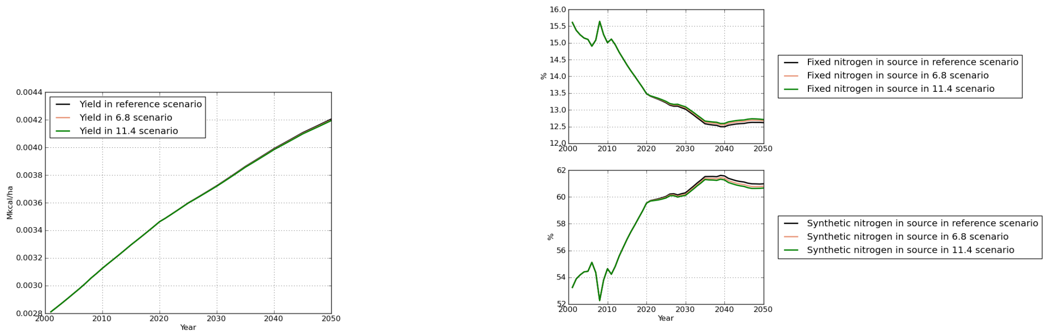

Figure 2: Yield, fertilizer share and fixed nitrogen share evolution in diet shift scenario and reference scenarios at global scale.

in 2010 to around 61% in 2050. For the biological fixation, the oppposite trend is observed with a decrease from 15% in 2010 to around 12.6% in 2050. The diet shift increase shaere of nitrogen from biological fixation but with in small proportion (less than 1 %). The intensification level described here by the crop yield is quite constant through scenario. Crops yields are ranged from 4.2 Mcal/ha for reference scenario to 4.19Mcal/ha for the 11.4 kag/cap/year legume scenario.(Fig.2)

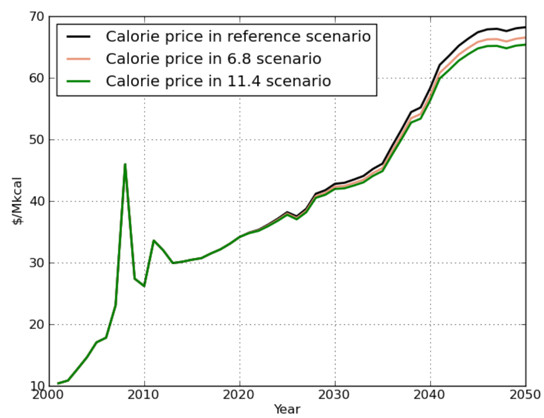

Figure 3: Calorie price evolution in diet shift scenario and reference scenarios at global scale.

In legumes scenario calorie price decreases from 68.2$ in the reference scenario to 66.5$ in the 6.8kg/cap/year legume scenario and 65.4$/cap/year legume scenario in 2050.(Fig.3).

The scale effect and the technological effects descreases calorie price. Scale effect is surpisingly small compared to technological effect. The scale effect represents change in vegetal demand which is slightly decrasing in legumes scenario. Feed demand decrease is indeed compensated by increase of legumes production. The technological effect represents price variation due to change of fixed nitrogen. Increase of fix nitrogen increase reduce calorie price by substituting expansive fertilizer by free fixed input. Finally composition effect increases slightly calorie price. Increase oflegumes in crop mix reduce yield of the representativ crop. It increases pressure on agricultural system and thus increases calorie price. In all these effects, the major one seems to be technological effect with substitution of fetilizer by green manure.

The net effect of the diet substitution is a decrease of 100 MtCO2eq/year in the 11.4kg/capita/year

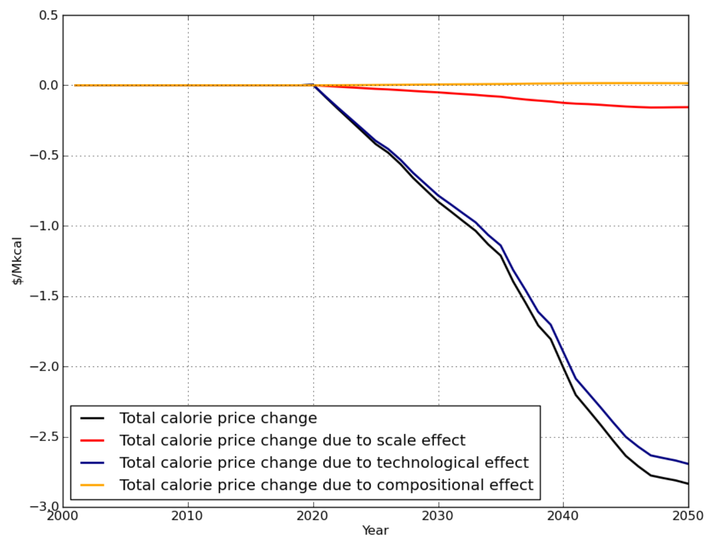

Figure 4: Calorie price decomposition in 11.4 kg/cap/year diet shift scenario at global scale.

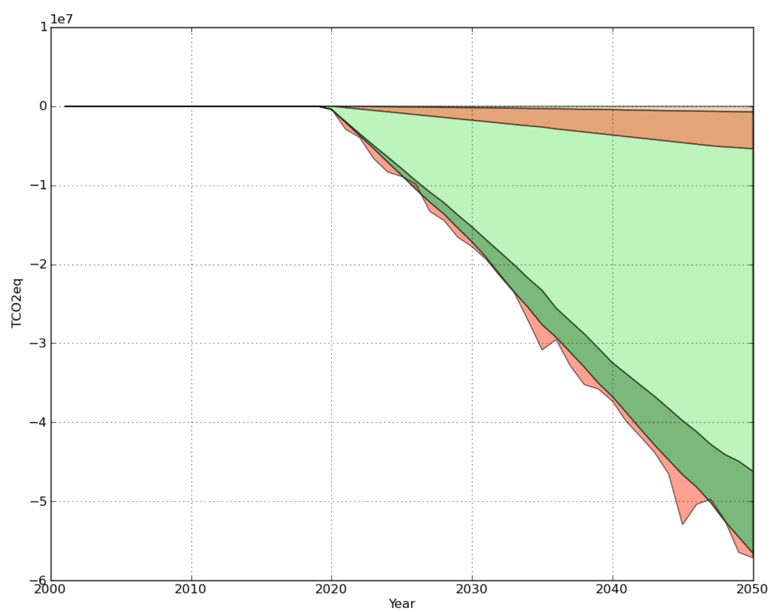

Figure 5: Emissions differences between diet shift scenario and reference scenarios at global scale.

scenario.(Fig.5) In the 11.4kg/capita/year scenario, scale effect reduces emissions by 600 MtCO2eq/year. The scale effect comes from the combination of (1) a reduction of animal calorie production by 30Tkcal/year which consequently decreases the production of food ruminant by around 7 Tkcal/year and (2) an increase of human vegetal consumption by 27 Tkcal/year (Fig. 6). The composition effect is the effect of the share of nitrogen biologically fixed by legumes in the overall production. Globally emissions decrease by around 50 MtCO2eq/year with this effect (Fig. 6). Finally, the technological effect takes into account global emission changes per nitrogen fixation. It includes indirect effect in the animal and vegetal systems. In the 11.4kg/capita/year scenario, this effect increases emissions by about 550 MtCO2/year.

Methane emissions and nitrous oxide emitted per ruminant calorie increase by 0.058 tCO2eq/Mkcal/year between 2020 and 2050 for the 11.4kg/capita/year scenario (Fig. 6). This increase is due to an extensification of animal production with a lower emission efficiency. Rice emissions are computed as the product of an emission factor per hectare and the cultivated land. Decrease of cultivated land (-9Mha in 2050 in the 11.4kg/capita/year scenario) leads to a small rice methane emissions decrease (-10.4 MtCO2eq in 2050 in the 11.4kg/capita/year scenario). Nitrogen applied on fields nitrous oxide emissions per calorie decrease (-4.08 MtCO2eq in 2050 in the 11.4kg/capita/year scenario). This is firstly due to the introduction of legumes. But there is also a change in intensification as the intensification level is based on the marginal cost (cf equation 3) and an increase of the biological fixation in nitrogen sources decreases marginal consumption of nitrogen by changing price ratios.

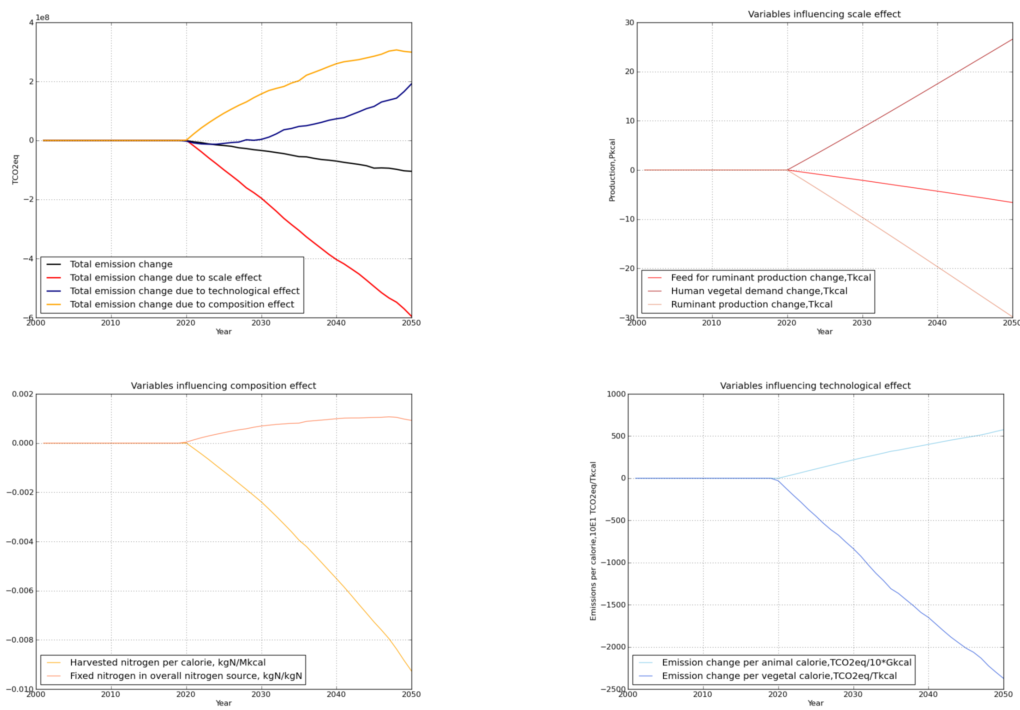

Figure 6: Decomposition of global emission change between legumes scenario and reference scenario. Evolution of variables influencing each effect in legumes scenario.

4 Discussion

Decrease of calorie price (Fig.3) is important to interpret results of a diet shift on emissions redutions. A reduction of price can indeed impacts demand by an increase of food demand. This "rebond effect" as currently described in economic litterature is not represented in the NLU model because demand are fixed by scenarios. Inclusion of this demand effect can decrease emissions benefits of a diet shift policy.

We chose to decompose emission changes due to the diet shift using a LMDI method instead of emission source decomposition. A LMDI decomposition is based on correlations between indicators and emissions and not based on processes. Here, we associated processes related to emissions changes and legumes to justify the relevance of the variable chosen in the decomposition. This method allows us to associate emission changes to the scale, composition and technological effects, by analogy. For example, a decrease of the cropland area reduces production according to constant or decreasing yields (Scale effect) and increases emissions per ruminant unit of production (Technologial effect). Even though the decomposition is very useful to understand the effects, it is still arbitrary to some extent, as other indicators could have been chosen. For instance, we have focused on the processes related to legumes, as a consequence, the effect of the composition and technology effects associated to changes in ruminant production are not explicited.

We compare our results with other diet change studies results in table 1: two land use model at global scale, MAgPIE and IMAGE (Popp et al., 2010; Stehfest et al., 2009), one scenario based modelling at european scale (Westhoek et al., 2015) and one using a global balance model, GlobAgri-WRR (Ranganathan et al., 2016). Ruminant meat change is converted in tonne of dry matter (tDM) for ruminant changes using FAO (2001) for energy content and protein content and 0.27 for dry matter content.

Emissions per quantity of substituted ruminant span a very wide range between 0.865 and 0.02 MtCO2eq/ktDM. The upper bound of this range is reached by the balance model GlobAgri-WRR. In this model, land-use change ultimately comes from forests or savannah. Sequestration of carbon is therefore much more important than in the NLU where land-use changes from cropland to pasture. In GlobAgri-WRR extensive and intensive systems are also reduced proportionally which leads to important reductions of production emissions.

Table 1: Comparison with other livestock substitution studies

Study	Emission type	Emission change MtCO2eq	Ruminant change	Ruminant change ktDM	Emission change MtCO2eq/ktDM
NLU	Production	103		5087	0.02
	LUC	1.05			
GlobAgri-WRR	Production	299	33% of ruminant in diet	4180	0.865
	LUC	3319			
Westhoek et al. 2014	Production	143	-50% beef and dairy, greening	6479	0.025
	LUC	25			
MAgPIE	Production	409	mediteranean diet	496	0.11
IMAGE	Production	2100	healthy diet	2300	0.16
	LUC	1700			

Because crop production increases, fossil fuel consumed by agricultural machines and pesticides production may increase, however the decrease in nitrogen synthesis caused by the increase of legumes nitrogen fixation would go in the reverse direction. These component were not evaluated in the current study owing to their lower shares in overall emissions and because they compensate, but they could be taken into account in future studies.

5 Conclusion

In Van Grinsven et al. (2015), a sustainable extensification is defined as a decrease of production per hectare along with a decrease of the overall pressure on agricultural land to avoid demand increase. The substitution of ruminant products by legumes is an attempt to trigger such a sustainable intensification, given that ruminant systems pressure on land through pastureland use and on GHG emissions is high. We show that even with such a policy, adverse effects may be taking place reducing the impacts of the mitigation policy. This result is a consequence of the hypothesis of forest areas being unresponsive to livestock production reduction in the NLU, that has two consequences. First there is no reforestation. Second, there is an increase of the share of the extensive system which is characterized by very low productivity and very high emissions per unit of production. The reduction of nitrous oxide crop emissions caused by decreasing fertilizer use following legumes introduction do not compensate for the livestock sector changes in term of emissions per unit of production. These results show that policies promoting pasture to forest conversion and aimed at reducing the decrease of livestock efficiency and the increase of emission per unit of production following decreases in livestock demand should be considered when promoting shift to legumes to get all the benefits of shifting diets.

Supplementary and material

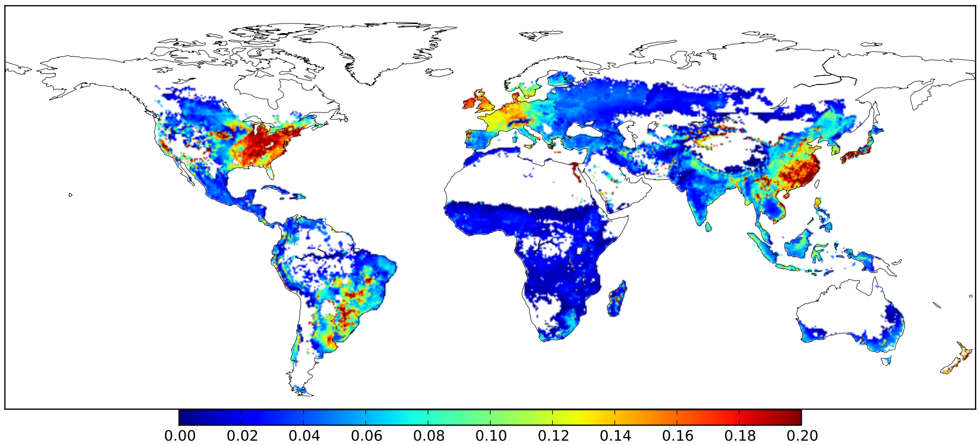

Figure 7: Nitrogen harvested for Ramankutty datas on land-use and LPJmL datas for yields of crops.

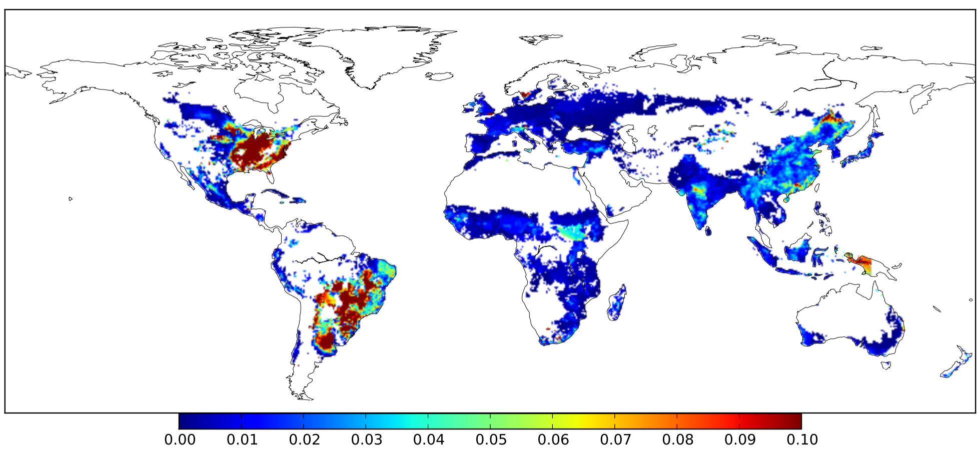

Figure 8: Biologically fixed nitrogen by legumes for Ramankutty datas on land-use and LPJmL datas for yields of crops.

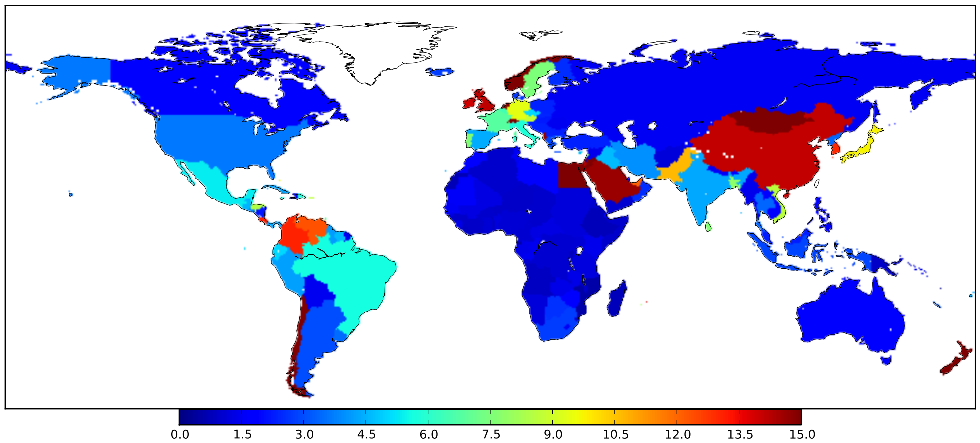

Figure 9: nitrous oxide emissions due to crops cultivation.

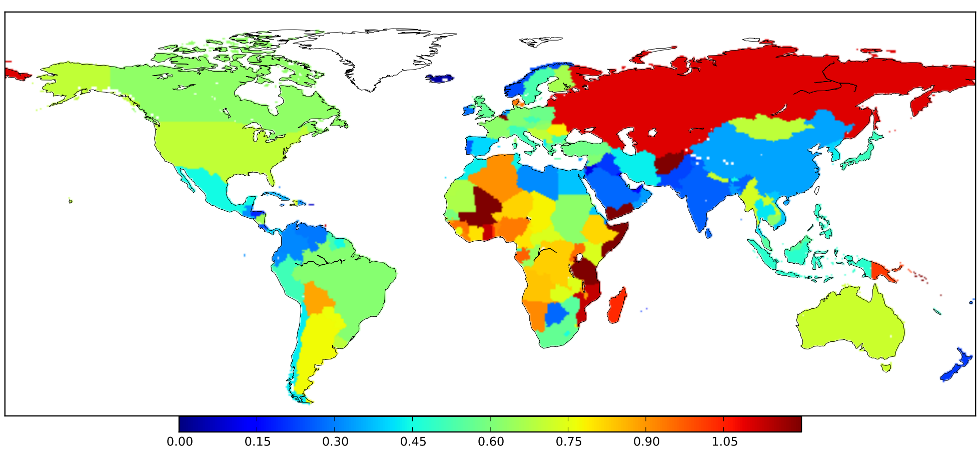

Figure 10: Nitrogen use efficiency based on Xin data at country scale.

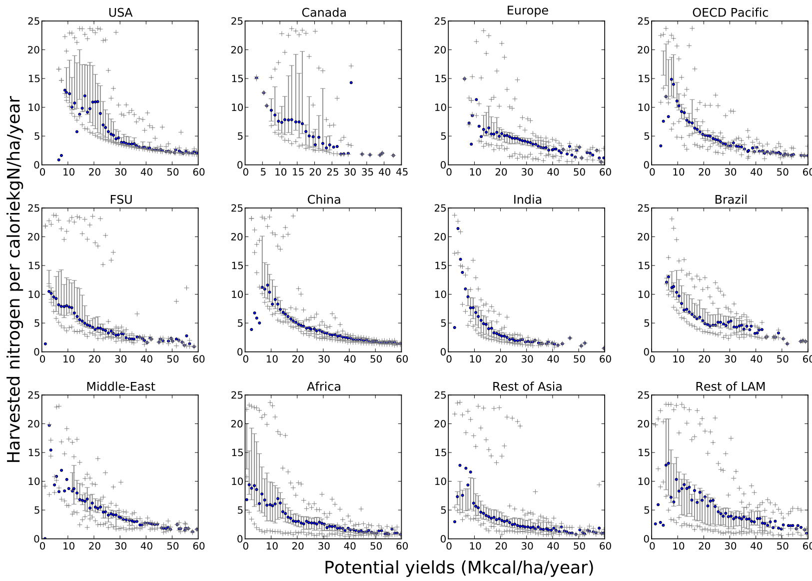

Figure 11: Mean harvested nitrogen per calorie and dispersion through land classes representing quality of land.

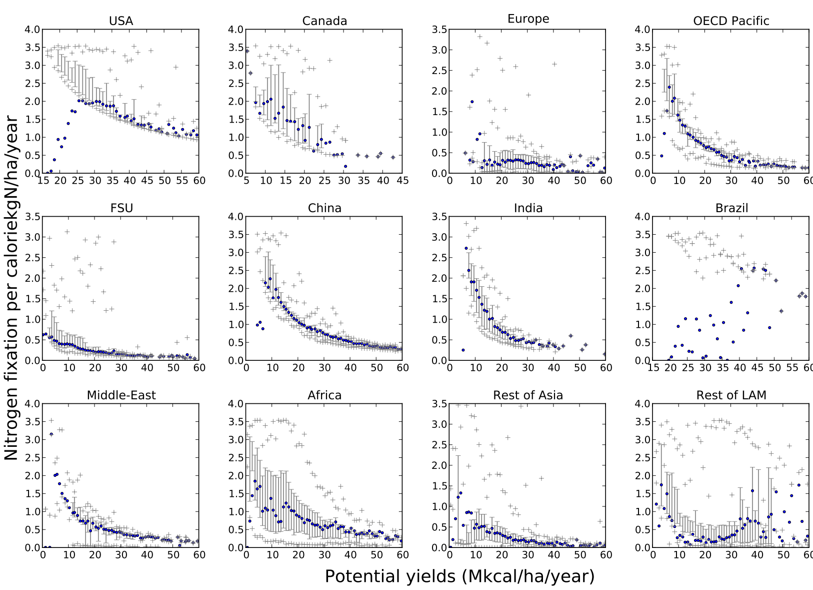

Figure 12: Mean biologically fixed nitrogen per calorie and dispersion through land classes representing quality of land.

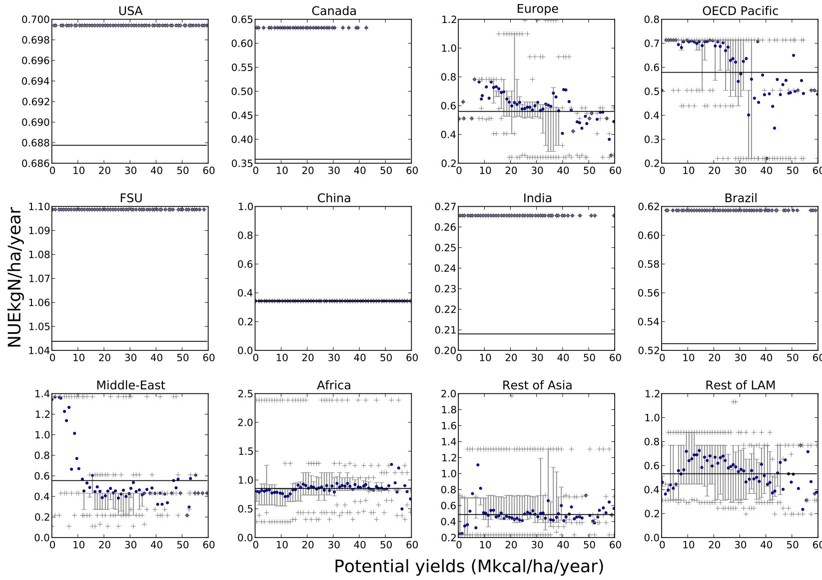

Figure 13: Mean nitrogen use efficiency and dispersion through land classes representing quality of land.

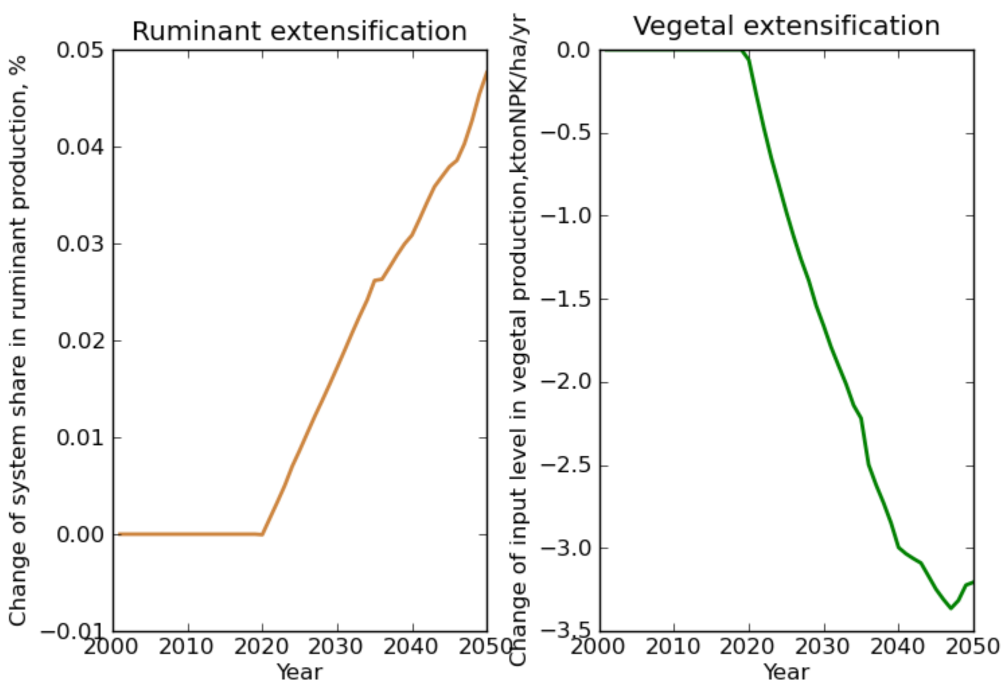

Figure 14: Extensification/Intensfication of animal and vegetal system

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